CLRCNTR: A Color Contour Plotting Routine for Displaying CFD-Generated Solutions

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A computer program for displaying flow-field color contour plots, generated from computational fluid dynamics (CFD) solutions, has been developed by extending the contour plotting option of the GENPLOT routine of Dr. R. G. Hindman. An algorithm for generating color-filled contour regions was developed for this extension and is described. The algorithm performs a detailed examination of the behavior of the dependent variable within the plotting domain to generate the contour regions and determines the relationship between these regions and their associated contour levels to assign the appropriate fill color to a particular region. Flow-field color contour plots generated from a hypersonic viscous shock-layer computation, a supersonic viscous blunt-fin computation, and a hypersonic viscous gas jet nosetip computation are presented to illustrate the capabilities and flexibility of the routine and to demonstrate that they can be used to aid the interpretation of CFD results.

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CLRCNTR: A Color Contour Plotting Routine for Displaying CFD-Generated Solutions

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PREFACE

The work reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC). The Air Force Program Managers were Dr. K. L. Kushman and Captain M. C. Towne, DOT. This work was performed by the Calspan Corporation, AEDC Division, operating contractor for the aerospace flight dynamics testing efforts at the AEDC, AFSC, Arnold Air Force Station, Tennessee. The work was performed in the von Kármán Gas Dynamics Facility (VKF) under AEDC Project Number DB97VA (Calspan Project Number V32A-CD). This report documents the development and application of CLRCNTR, a computer program for displaying flow-field color contour plots generated from computational fluid dynamics (CFD) solutions. The research was performed from October 1, 1985 through September 30, 1986, and the manuscript was submitted for publication October 7, 1986.

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ILLUSTRATIONS

1.0 INTRODUCTION

1.1 MOTIVATION

It has long been recognized that flow visualization plays an important role in the understanding of complex fluid-flow behavior. Mach (Ref. 1) published, in 1887, the first photographs of a bow shock wave visualized by the schlieren technique, and he photographed a bullet in supersonic flight in 1893 with a device that is now known as the Mach-Zehnder interferometer. Reynolds (Ref. 2) used dyes during experiments in which he determined that the transition from laminar to turbulent flow occurs at a critical value of the Reynolds number (Re_{cr}). Prandtl and Tietjens (Ref. 3) used aluminum dust particles to visualize boundary-layer separation, and Wieselsberger (Ref. 4) used smoke to "see" the point of separation move downstream in the classical experiment of flow past a sphere to which a thin wire is attached to trip the boundary layer. Van Dyke (Ref. 5) has compiled numerous flow visualization photographs into a bound volume. They serve as excellent examples of the information that can be gleaned from visual experiments.

With the advent of the supercomputer, the fluid dynamicist now has the capability to use complex numerical techniques to solve approximations to the partial differential equations of fluid motion in a timely and efficient manner. At the AEDC, the approximations must be of such quality that when used in conjunction with experimental results accurate flow predictions for test planning, test data validation, and extrapolation of test facility results to flight conditions can be provided. In view of the fact that flow visualization is essential to the understanding and interpretation of experimental fluid dynamic results, it is also necessary to generate a picture of the computational results to comprehend the flow field created by the numerical simulation and to verify the correctness of the solution. Displaying the results from CFD codes using computer graphics generally is considered to be the most practical method to view and examine the solution of a computation. Deiwert and Rothmund (Ref. 6), for example, used computer graphics to examine the results of a three-dimensional (3-D) flow computation over a conical afterbody containing a jet. The oblique shock wave generated by the expanding jet plume, and the slip surface between the free stream and the jet were easily perceived. Chaussee, Rizk, and Buning (Ref. 7) analyzed a viscous flow computation over a space shuttle orbiter-like configuration using computer graphics, and Hung and Buning (Ref. 8) investigated the shock wave/boundary-layer interaction induced by a blunt fin protruding from a flat plate using CFD results in conjunction with computer graphics. Because of the complexity of these flow fields, the use of color helps to maintain the graphic clarity. Color helps the individual to differentiate objects and/or flow features. In addition, color facilitates interpretation by making flow gradients and embedded regions readily apparent. Buning and Steger (Ref. 9) give an excellent overview of the importance

of using computer graphics for displaying the results from CFD codes. They also discuss the need for advanced algorithms that automate the process of searching for significant flow attributes through huge CFD databases and the need for powerful computer graphics workstations that have the capability to rotate and translate three-dimensional graphic images in real time.

The objective of this report is to document the development and application of a computer program for displaying flow-field color contour plots generated from CFD solutions. The program has been interfaced with several CFD codes at AEDC, and typical results are presented.

1.2 BACKGROUND

An unpublished computer program was written by Dr. R. G. Hindman, currently with Iowa State University, to display graphically solutions generated by the modified Hung-MacCormack two-dimensional (2-D) Navier-Stokes compression ramp code (Ref. 10). The program, coined GENPLOT, is a highly flexible monochrome plotting routine that graphically reproduces the computational mesh, the computed velocity field in vector form, flow-field contour maps, and boundary data plots at the user's request. An effort was initiated at the AEDC in 1983 to develop a user-friendly color contour plotting program to be used routinely with CFD codes. This was accomplished by exploiting the work of Hindman and adopting state-of-the-art computer graphics hardware devices and software packages to enhance the features of the flow-field contour plotting option of GENPLOT. The resultant plotting routine, called CLRCNTR, uses the basic program architecture, contour generating logic, and input/output requirements of GENPLOT.

2.0 PROGRAM DEVELOPMENT

2.1 ASSUMPTIONS AND CONCEPTS

The basic assumptions made by CLRCNTR are that the input flow solution is generated by a perfect-gas computation and that the plotting domain is two-dimensional and is enclosed by four boundaries. These boundaries are considered to be part of the plotting domain and can be, for example, solid surfaces, planes of symmetry, inflow/outflow planes, or the outer edge of the computational domain. The input flow solution can be generated from either a 2-D or a 3-D simulation; however, if it is generated from a 3-D simulation, a 2-D slice through this flow field must be selected and defined as the plotting domain. The plotting domain must be configured in the following form:

```
J =              1  2  3  4  5  .  .  .  .  .  .  .  .  .  .      JMAX
K = KMAX         +  +  +  +  +  +  +  +  +  +  +  +  +  +  +     K = KMAX
    .            +  +  +  +  +  +  +  +  +  +  +  +  +  +  +       .
    .            +  +  +  +  +  +  +  +  +  +  +  +  +  +  +       .
    .            +  +  +  +  +  +  +  +  +  +  +  +  +  +  +       .
    .            +  +  +  +  +  +  +  +  +  +  +  +  +  +  +       .
    .            +  +  +  +  +  +  +  +  +  +  +  +· +  +  +       .
    .            +  +  +  +  +  +  +  +  +  +  +  +  +  +  +       .
    .            +  +  +  +  +  +  +  +  +  +  +  +  +  +  +       .
    .            +  +  +  +  +  +  +  +  +  +  +  +  +  +  +       .
    .            +  +  +  +  +  +  +  +  +  +  +  +  +  +  +       .
    .            +  +  +  +  +  +  +  +  +  +  +  +  +  +  +       .
    .            +  +  +  +  +  +  +  +  +  +  +  +  +  +  +       .
K = 5            +  +  +  +  +  +  +  +  +  +  +  +  +  +  +     K = 5
K = 4            +  +  +  +  +  +  +  +  +  +  +  +  +  +  +     K = 4
K = 3            +  +  +  +  +  +  +  +  +  +  +  +  +  +  +     K = 3
K = 2            +  +  +  +  +  +  +  +  +  +  +  +  +  +  +     K = 2
K = 1            +  +  +  +  +  +  +  +  +  +  +  +  +  +  +     K = 1
J =              1  2  3  4  5  .  .  .  .  .  .  .  .  .  .      JMAX
```

where $J = 1$ to JMAX are, for example, the number of grid points along a body surface over which the flow field is computed, and $K = 1$ to KMAX are the number of grid points normal to this surface. The user must input the flow solution in a form that is consistent with this domain. The physical coordinates of each grid point and the solution vector at each grid point are then defined on this domain. The x and y coordinates of the grid points geometrically define the plane of the plotting domain, and the z coordinate is assumed to be normal to this surface. This coordinate system does not necessarily have to coincide with the coordinate system that is defined in the CFD code. The solution vector is of the form ϱ, ϱu, ϱv, ϱw, e_t where ϱ is the local density; ϱu, ϱv, and ϱw are the x, y, and z components of momentum, respectively; and e_t is the local total energy per unit volume of the flow. The solution vector defines the flow in its entirety, within the assumptions made in the CFD code, and other parameters may be computed from it. These parameters are specified by executing an interactive interrogation program prior to executing CLRCNTR. They must be selected from the following menu:

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Parameter	Normalization Parameter
Static Pressure Coefficient	-----
Static Pressure	$\varrho_\infty U_\infty^2$
Density	ϱ_∞
u-Velocity	U_∞
v-Velocity	U_∞
w-Velocity	U_∞
Static Temperature	T_{0_∞}
Entropy	$s_\infty \gamma M_\infty^2$
Total Enthalpy	H_{0_∞}
Total Pressure	$\varrho_\infty U_\infty^2$
Total Velocity	U_∞
Magnitude of Vorticity	U_∞
Stream Function (2-D or Axisymmetric Flow Solution Only)	$\varrho_\infty U_\infty$
Local Mach Number	-----
User-Defined Parameter	-----

The parameters are normalized as shown if the solution vector is nondimensionalized as follows:

$$\varrho/\varrho_\infty$$
$$\varrho u/\varrho_\infty U_\infty$$
$$\varrho v/\varrho_\infty U_\infty$$
$$\varrho w/\varrho_\infty U_\infty$$
$$e_t/\varrho_\infty U_\infty^2$$

The interrogation program also prompts the user for plot labels, label heights, and contour levels and requests if the user wants a legend displayed. A subset of the plotting domain also may be specified during execution of this program. In addition, one of four options may be selected to specify the contour levels; they are

1. plot "n" contour levels between the selected domain maximum and minimum values,
2. plot "n" contour levels between user-specified maximum and minimum values,
3. plot "n" user-specified contour levels, and
4. plot contour levels given by the equation

$$\text{min} + (I - 1) \times \text{delta} \tag{1}$$

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for I = 1,N, where N = (max-min)/delta and min, max, and delta are user inputs. The input supplied to the interrogation program is stored on an input file for subsequent use by CLRCNTR.

2.2 GENERATION OF CONTOUR LINES

Contour lines, by definition, must either start and end at any of the four boundaries that enclose the plotting domain or must start and end within the boundaries and close back on themselves. It is not a difficult task to determine the location of the contour lines if the value of the function that is to be plotted is known at each of the grid points in the domain and if the levels of the contour lines are specified. For each contour level, this procedure is as follows:

CLRCNTR begins at the grid point defined by the indices (J = 1,K = 1) and examines the behavior of the function along the K = 1 boundary. When the value of the function at the grid point (J,K = 1) is less than the current contour level, and the value of the function at the grid point (J + 1,K = 1) is greater than the current contour level, a linear interpolation is performed to determine the approximate starting location of the contour line on this boundary. The procedure then moves into the grid cell defined by the corner points (J,K = 1), (J + 1,K = 1), (J + 1,K = 2), and (J,K = 2). An average value of the function is computed from the values at each of the corner points, and this average is presumed to be located at a point defined by the intersection of the two lines that bisect opposite sides of the cell. CLRCNTR then examines the behavior of the function between this averaged point and the corner points (J,K = 1) and (J + 1,K = 1). The contour line must cross either the line segment constructed between the averaged point and the point (J,K = 1) or the line segment constructed between the averaged point and the point (J + 1,K = 1). After the appropriate segment is established, a linear interpolation is performed again to determine the approximate crossing location of the contour line. CLRCNTR continues to monitor the behavior of the function within the current grid cell by examining the mathematical relationship between the averaged point and the corner points (J,K = 2) and (J + 1,K = 2). The relationship between adjacent corner points is examined also, and the contour line exits from the grid cell if it can; however, if it does not exit from the cell, additional line segments must be constructed between the averaged point and the corner points (J,K = 2) and (J + 1,K = 2). The appropriate crossing location is then determined by linear interpolation. This procedure continues until the contour line exits the current grid cell. After leaving the cell, the contour line either enters an adjacent grid cell, or ends on the originating boundary. If it enters an adjacent cell, the above procedure is repeated using the four corner points

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that define this cell. CLRCNTR moves from grid cell to grid cell "tracing" the contour line through the plotting domain until a boundary is reached. The program then returns to the starting boundary of the contour line where it continues to "look" for additional contour lines having levels that are equivalent to the current contour level. After the K = 1 boundary is exhausted, CLRCNTR moves to the J = JMAX boundary, and the procedure is repeated. After all four boundaries are examined for the start of contour lines that have levels equivalent to the current contour level, CLRCNTR moves to the interior (i.e. off the boundaries) of the plotting domain and searches for contour lines that close back on themselves. The internal grid cell procedure described earlier is used, employing local cell corner points. All contour lines within the resolution of the plotting domain and having a functional value equivalent to the current contour level are generated at the completion of this procedure. The entire procedure is repeated for subsequent contour levels until all levels are depleted.

2.3 GENERATION OF CONTOUR REGIONS

A contour region is defined as that region that is enclosed by one or more plotting domain boundaries and one or more contour lines that have the same contour level. (The one exception to this definition is a contour line that closes back on itself; a contour line of this type implicitly defines a contour region.) Each contour region is determined by specifying the points along the boundary of this region. For each contour level, these points are determined by using the following procedure:

CLRCNTR begins at the grid point defined by the indices (J = 1,K = 1) and searches along the K = 1 boundary for the first point of a contour line that has a value equivalent to the current contour level. The searching will continue on the J = JMAX boundary if the first point is not found on the K = 1 boundary. When this point is located, the next grid point on the local plotting domain boundary becomes the first point on the boundary of the contour region. For example, if the first point of the contour line is between the grid points (J,K = 1) and (J + 1,K = 1), the first point on the boundary of the contour region is the grid point (J + 1,K = 1). CLRCNTR now begins to search for the last point of this contour line starting from the current location, for example, the point (J + 1,K = 1). The searching will continue on the J = JMAX boundary if the last point is not found on the K = 1 boundary. All plotting domain boundary points become contour region boundary points until either the last point of the contour line is located or until the first point of a second contour line that has a value equivalent to the current contour level is found. If the first point of a second contour line is found before the last point

of the first contour line is located, the points that define the second contour line become points on the boundary of the contour region that is being generated. The second contour line terminates at one of the four plotting domain boundaries. CLRCNTR continues to search for the last point of the first contour line starting from this location. All plotting domain boundary points continue to become contour region boundary points. If subsequent contour lines that have a value equivalent to the current contour level are encountered before the last point of the first contour line is located, the points that define these lines also become points on the boundary of the current contour region. These subsequent contour lines terminate at a plotting domain boundary. CLRCNTR continues to search for the last point of the first contour line starting from this location. The region is completed after this point is found. The points that define the first contour line become contour region boundary points, and the region is closed with the first point of the first contour line. After this region is completed, CLRCNTR searches for any remaining contour lines at the current contour level and generates additional contour regions as required. The entire procedure is repeated for subsequent contour levels until all levels are depleted.

2.4 CONTOUR REGION AREA COMPUTATION AND ASSIGNMENT OF COLORS

The contour regions must be displayed in a specific sequence to construct the entire flow-field contour plot correctly. A simple example illustrating the problem that can be encountered if the regions are displayed in a random sequence is the embedding of one contour region within another. If a smaller region is embedded within a larger one, and the smaller region is displayed first, it will be erased when the larger region is displayed on top of it. This problem is resolved by displaying the region that has the larger area before displaying the region that has the smaller area. The areas are computed by applying Green's theorem to each contour region and evaluating the resulting line integral around its boundary.

The number of colors defined in the CLRCNTR color spectrum is always one greater than the specified number of contour levels. The number of colors that are actually available depends on the graphics hardware device that is used to display the plot. A color is assigned to a contour region based on the level of the contour line that generates that region. The increment in contour level that is used to assign the proper color to a contour region is calculated from the following equation:

$$\text{Increment} = (\text{max level} - \text{min level})/(\text{no. of levels} - 1) \tag{2}$$

Because colors are assigned to contour regions and not to contour levels, all regions associated with the highest contour level are assigned the last color of the color spectrum. (All regions

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associated with the lowest contour level could have been assigned the first color of the color spectrum just as easily.) Assigning the colors using this technique results in color two being assigned to the contour regions generated from contour level one, color three being assigned to the contour regions generated from contour level two, ..., and color $n + 1$ being assigned to the contour regions generated from contour level n. The entire plotting domain is displayed first, and it is assigned a color that is associated with regions that are generated from contour levels that are less than the lowest contour level that is either specified or found, depending on which contour level specification option is selected. The relationship between contour levels, contour regions, and assigned colors is as follows:

Contour Level	1	2	3...		n−1	n	
Low End of Color Spectrum	Contour Regions from Levels <1	Contour Regions from Level 1	Contour Regions from Level 2	...	Contour Regions from Level n−1	Contour Regions from Level n	High End of Color Spectrum
Color	1	2	3	...	n	n+1	

Another way of interpreting this relationship is that contour regions that are generated from a specific contour level are always defined to be on the side of the associated contour line that is in the positive gradient direction of the function that is being plotted (i.e., moving toward the low end of the color spectrum is associated with a negative gradient of the function, and moving toward the high end of the color spectrum is associated with a positive gradient of the function). The method that is used to generate contour regions from contour lines, except for those regions that are generated from contour lines that close back on themselves, inherently assures that these regions are assigned a color that is consistent with the relationship between contour levels, contour regions, and assignment of colors. For regions that are generated from contour lines that close back on themselves, the proper color is assigned by using the following procedure:

The derivative of the function that is being plotted is computed along a unit normal vector assumed to point in the outward direction (i.e. away from the center of the contour region in question) at a random location on the associated closed contour line. If the area of the region, computed as described earlier, is greater than zero, then the assumed direction of the unit normal vector is correct. If the area of the region is less than zero, then the direction of the unit normal vector is toward the center of the contour region in question. The direction of this derivative characterizes the behavior of the function in the neighborhood of the closed contour line, and the proper color is assigned to the associated region.

3.0 PROGRAM APPLICATIONS

CLRCNTR has been interfaced with several CFD codes at the AEDC, and three applications are presented. All CFD computations were performed on the AEDC CRAY® X-MP/12 computer.

3.1 HYPERSONIC VISCOUS SHOCK-LAYER FLOW OVER A HEMISPHERE

A hypersonic viscous shock-layer, perfect-gas computation was performed over a hemisphere immersed in a Mach 22 free stream using the CVEQ (Ref. 11) code. The wall enthalpy to free-stream total enthalpy ratio was 0.13, and the free-stream static temperature was 390°R. The free-stream Reynolds number, based on nose radius, was 870,000. CVEQ is a computer code capable of solving the viscous shock-layer equations for the laminar flow of a perfect gas or air in thermodynamic equilibrium over a hemisphere in a supersonic or hypersonic free stream.

3.2 SUPERSONIC VISCOUS FLOW OVER A BLUNT FIN PROTRUDING FROM A FLAT PLATE

The three-dimensional, time-dependent, Navier-Stokes code, BLUNTFIN (Ref. 12), was used to compute the flow field over a blunt fin protruding from a flat plate immersed in a Mach 2.95 free stream. The configuration is identical to the configuration used by Hung and Buning (Ref. 8). The free-stream Reynolds number, based on fin width, was 271,000, and the free-stream static temperature was 195°R. An adiabatic wall condition was invoked during the computation. BLUNTFIN, a time-dependent, finite-volume computer code written in generalized body-fitted coordinates, is capable of predicting the viscous, compressible flow over a 3-D arbitrary geometry.

3.3 HYPERSONIC VISCOUS GAS JET NOSETIP FLOW FIELD

The flow field resulting from a sonic nose jet issuing counter to a Mach 15.8 free stream was computed using the gas jet nosetip (GJNT) code of Fox (Ref. 13). The nose jet was at 1-deg angle-of-attack relative to the free-stream velocity. The free-stream unit Reynolds number was 106,000,000 per foot, and the free-stream static temperature was 520°R. An adiabatic wall condition was invoked during the computation, and the gas jet total pressure divided by the total pressure downstream of a normal shock at a free-stream Mach number of 15.8 was 1.15. GJNT is a computer code capable of solving the three-dimensional, time-dependent, thin-layer Navier-Stokes equations for the laminar or turbulent flow field resulting from a

sonic nose jet issuing counter to a supersonic or hypersonic free stream. The code uses shock fitting to determine the location of the bow shock and dynamically adjusts the outer edge of the computational domain to coincide with the bow shock.

4.0 DISCUSSION OF RESULTS

DISSPLA (Ref. 14) plotting software was used in the CLRCNTR computer program, making the routine virtually hardware-device independent. All plots were generated on the Tektronix® 4115B color graphics workstation; display time was approximately 4 min per plot. Contour level option "1" was used, and thirteen contour levels were specified for all applications. Execution time for CLRCNTR was less than 60 sec on the CRAY X-MP/12 computer.

Contour plots of normalized static pressure, static temperature, stream function, local Mach number, total velocity, and total pressure are presented in Fig. 1 for the hypersonic viscous shock-layer flow over a hemisphere. Starting from the lower left corner of the plot and moving in a counter-clockwise direction, the four plotting domain boundaries are (1) the hemisphere axis-of-symmetry at the stagnation point, (2) the surface of the hemisphere, (3) the outflow plane at the shoulder of the hemisphere, and (4) the bow shock. The expansion of the flow around the hemisphere is easily perceived by observing, for example, the static pressure and static temperature plots. The interface lines between the different colors in the stream function plot represent the stream lines of the flow, and the difference in magnitude between two adjacent interface lines (i.e. stream lines) is a measure of the mass rate of flow between these two lines. The approximate location of the sonic line can be determined from the local Mach number plot. The stagnation region is visible in the total velocity plot, and the total pressure plot reveals a decreasing shock strength from the hemisphere axis-of-symmetry to the outflow plane.

The results of the blunt-fin application are presented in Figs. 2 and 3. Contour plots of normalized static pressure, density, static temperature, and local Mach number on the fin plane-of-symmetry are shown in Fig. 2. Starting from the lower left corner of the plot and moving in a counter-clockwise direction, the four plotting domain boundaries are (1) the surface of the flat plate, (2) the leading edge of the fin, (3) the outer edge of the computational domain, and (4) the inflow plane. The same parameters are plotted on the surface of the flat plate and are shown in Fig. 3. Starting from the lower left corner of this plot and moving in a counter-clockwise direction, the four plotting domain boundaries are (1) the fin plane-of-symmetry, (2) the surface of the blunt fin, (3) the outflow plane, and (4) the inflow plane. The important flow features to observe in the static pressure contour plot of Fig. 2 are the existence of a peak pressure on the fin leading edge, the appearance of an extreme low-pressure

region below this peak pressure, and an increase in the pressure toward the plate surface below this low-pressure region. Flow attributes related to these features are visible in the density, static temperature, and local Mach number contour plots on the fin plane-of-symmetry. In addition, embedded regions of lower static temperature and higher local Mach number appear, in their respective plots, upstream of the fin leading edge near the flat plate surface. Hung and Buning (Ref. 8) suggest that this behavior results from the presence of two embedded, reverse-flow, supersonic zones—one on the fin and another on the plate. They also suggest that the existence of these embedded regions is traced to a horseshoe vortex occurring in the flow field. The fin bow shock and its effect on the incoming flow are visible in the contour plots of Fig. 3. The bow shock causes the boundary layer on the flat plate to separate from the plate surface ahead of the fin, resulting in a separated flow region. This region consists of a lambda shock in the plane-of-symmetry and a horseshoe vortex near the plate surface. The lambda shock impinges on the fin bow shock and causes the increase in static pressure, density, and static temperature on the fin leading edge, observed in the symmetry plane contour plots of Fig. 2.

The results of the gas jet nosetip application are presented in Fig. 4. Starting from the lower right corner of the plot and moving in a clockwise direction, the four plotting domain boundaries are (1) the fitted bow shock; (2) the leeside outflow plane; (3) the leeside surface of the nosetip, the jet exit plane, and the windside suface of the nosetip; and (4) the windside outflow plane. The plotting domain is generated in the pitch plane-of-symmetry of the flow field. The free stream is compressed as it crosses the bow shock and perceives the nose jet as a protrusion. The nose jet first expands upstream from the exit plane and then is compressed until it stagnates against the incoming flow where it is turned downstream. The free stream, after being compressed subsonically by the bow shock, expands around the protrusion of the jet and accelerates down the body. A recirculating flow region is visible at the lip of the nosetip surface adjacent to the jet exit plane on both the windside and the leeside of the configuration. The flow attaches to the nosetip surface downstream of this region. The cooling effect of the gas jet is apparent from the normalized total enthalpy plot, where it is observed that the nosetip surface is sheathed by a relatively low-energy fluid layer.

5.0 CONCLUDING REMARKS

A computer program has been developed for displaying flow-field color contour plots generated from CFD solutions. The results from three different CFD codes have been presented to illustrate the capabilities and flexibility of the plotting routine. It is concluded that the program can adequately generate color contour plots of the flow field predicted by CFD codes and that these plots can be used effectively to interpret and evaluate the CFD results.

In addition, it is concluded that color helps to maintain the graphic clarity of the plot and facilitates the interpretation of the results by highlighting significant features of the flow.

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CONTOURS OF PRESSURE

LT 0.103708
GE 0.103708 LT 0.167123
GE 0.167123 LT 0.230538
GE 0.230538 LT 0.293953
GE 0.293953 LT 0.357368
GE 0.357368 LT 0.420783
GE 0.420783 LT 0.484198
GE 0.484198 LT 0.547613
GE 0.547613 LT 0.611028
GE 0.611028 LT 0.674444
GE 0.674444 LT 0.737859
GE 0.737859 LT 0.801274
GE 0.801274 LT 0.864689
GE 0.864689

FLOW OVER A HEMISPHERE...MINF=22, RN=0.40 INCHES
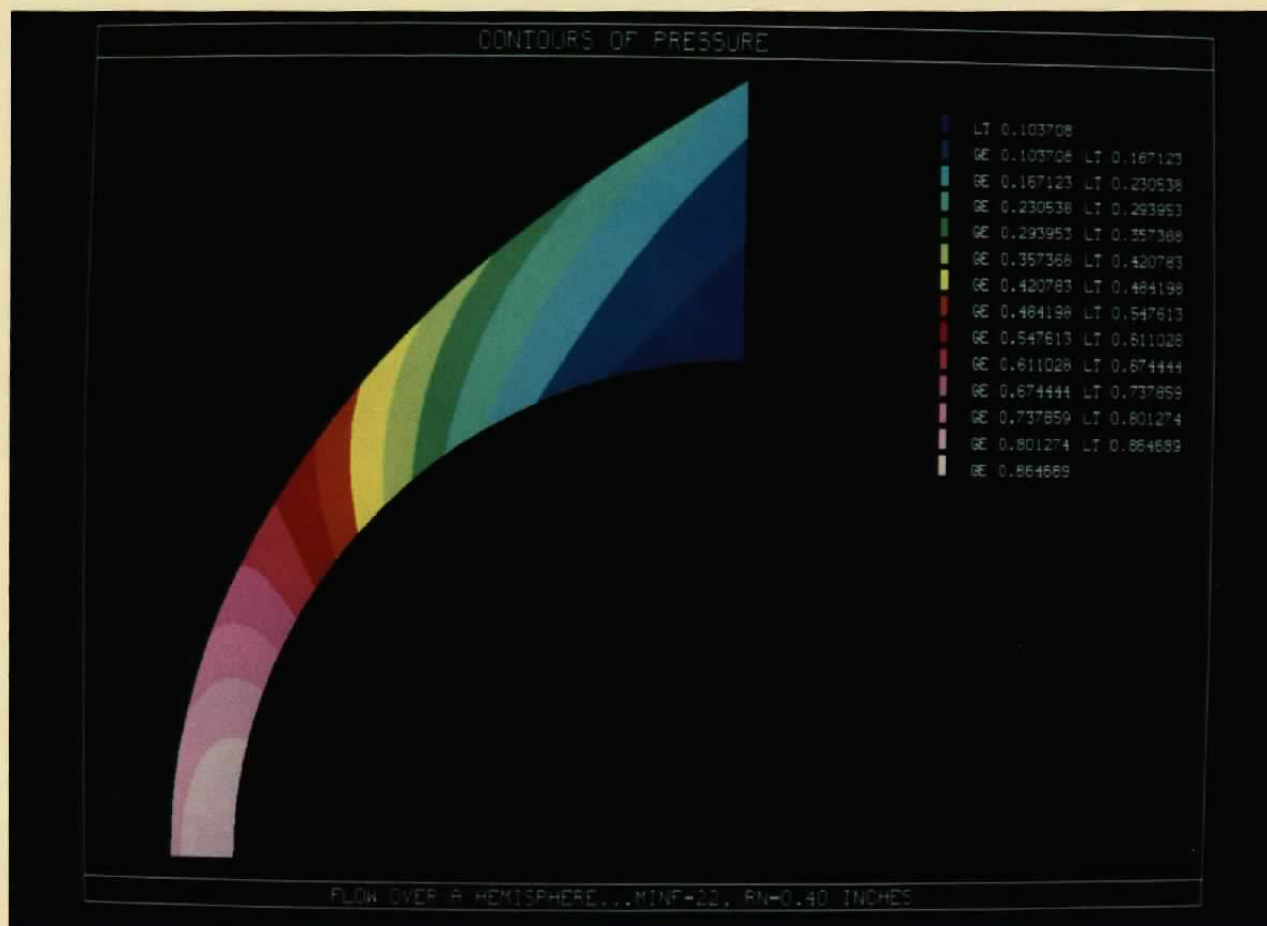
A E D C
14296-86

a. Normalized static pressure
Figure 1. Hypersonic viscous shock-layer flow over a hemisphere.

CONTOURS OF TEMPERATURE

FLOW OVER A HEMISPHERE...MINF=22, RN=0.40 INCHES
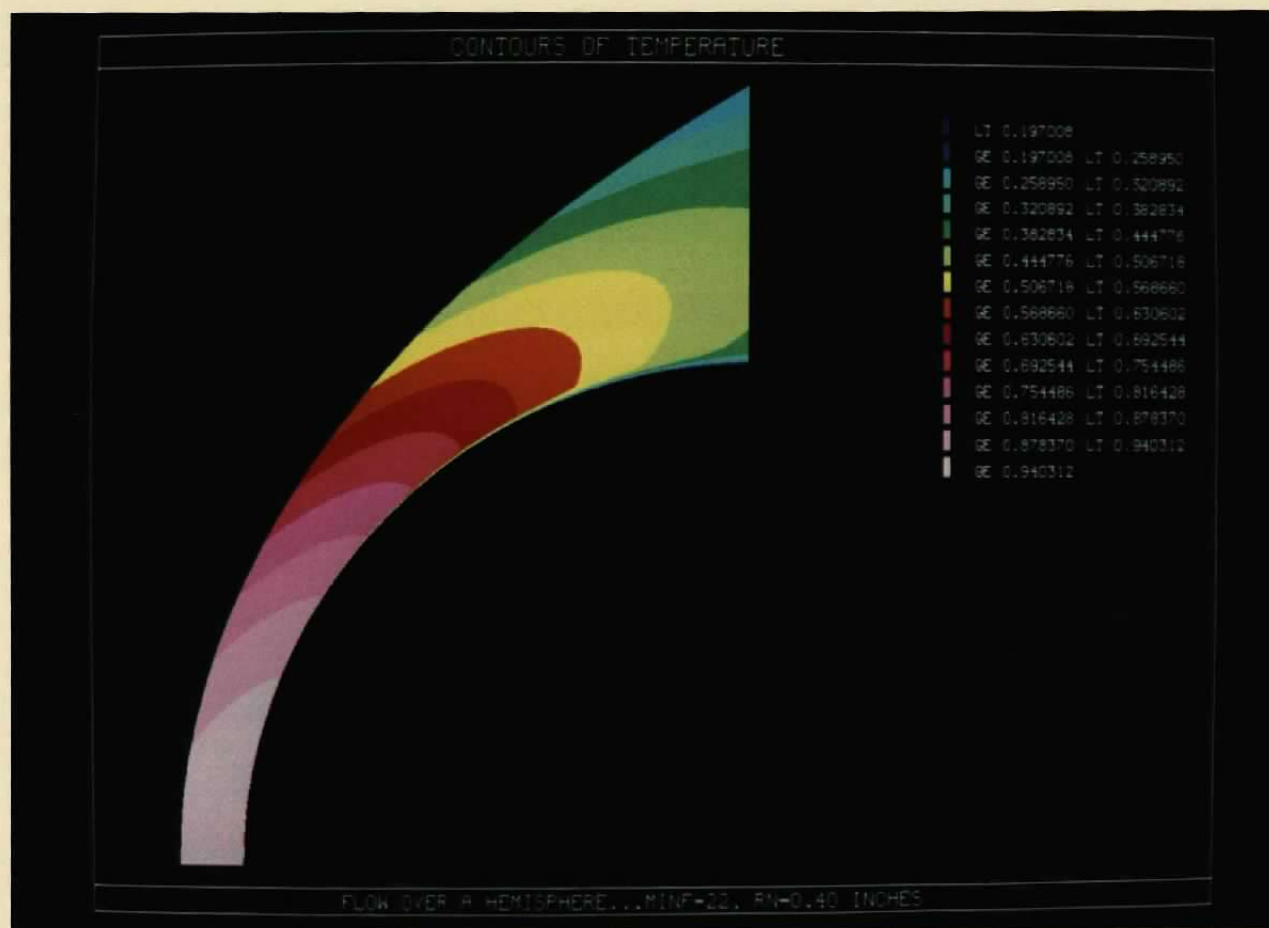
AEDC
14298-86

b. Normalized static temperature
Figure 1. Continued.

AEDC-TR-86-40

CONTOURS OF STREAM FUNCTION

	LT 0.083060
	GE 0.083060 LT 0.166420
	GE 0.166420 LT 0.249780
	GE 0.249780 LT 0.333140
	GE 0.333140 LT 0.416500
	GE 0.416500 LT 0.499861
	GE 0.499861 LT 0.583221
	GE 0.583221 LT 0.666581
	GE 0.666581 LT 0.749941
	GE 0.749941 LT 0.833301
	GE 0.833301 LT 0.916661
	GE 0.916661 LT 1.000021
	GE 1.000021 LT 1.083381
	GE 1.083381

FLOW OVER A HEMISPHERE...MINF=22, RN=0.40 INCHES

c. Normalized stream function
Figure 1. Continued.

CONTOURS OF MACH NUMBER

LT 0.271048
GE 0.271048 LT 0.542092
GE 0.542092 LT 0.813136
GE 0.813136 LT 1.084180
GE 1.084180 LT 1.355224
GE 1.355224 LT 1.626268
GE 1.626268 LT 1.897312
GE 1.897312 LT 2.168356
GE 2.168356 LT 2.439400
GE 2.439400 LT 2.710444
GE 2.710444 LT 2.981488
GE 2.981488 LT 3.252533
GE 3.252533 LT 3.523577
GE 3.523577

FLOW OVER A HEMISPHERE...MINF=22, RN=0.40 INCHES

AEDC
14300-86

d. Local Mach number
Figure 1. Continued.

25

AEDC-TR-86-40

CONTOURS OF TOTAL VELOCITY

LT	0.062497
GE 0.062497	LT 0.124993
GE 0.124993	LT 0.187489
GE 0.187489	LT 0.249985
GE 0.249985	LT 0.312481
GE 0.312481	LT 0.374977
GE 0.374977	LT 0.437473
GE 0.437473	LT 0.499970
GE 0.499970	LT 0.562466
GE 0.562466	LT 0.624962
GE 0.624962	LT 0.687458
GE 0.687458	LT 0.749954
GE 0.749954	LT 0.812450
GE 0.812450	

FLOW OVER A HEMISPHERE...MINF=22, RN=0.40 INCHES

A E D C
14311-86

AEDC-TR-86-40

e. Normalized total velocity
Figure 1. Continued.

CONTOURS OF TOTAL PRESSURE

LT 1.839224
GE 1.839224 LT 3.638050
GE 3.638050 LT 5.436875
GE 5.436875 LT 7.235700
GE 7.235700 LT 9.034526
GE 9.034526 LT 10.833351
GE 10.833351 LT 12.632176
GE 12.632176 LT 14.431002
GE 14.431002 LT 16.229827
GE 16.229827 LT 18.028652
GE 18.028652 LT 19.827478
GE 19.827478 LT 21.626303
GE 21.626303 LT 23.425129
GE 23.425129

FLOW OVER A HEMISPHERE...MINF=22, RN=0.40 INCHES
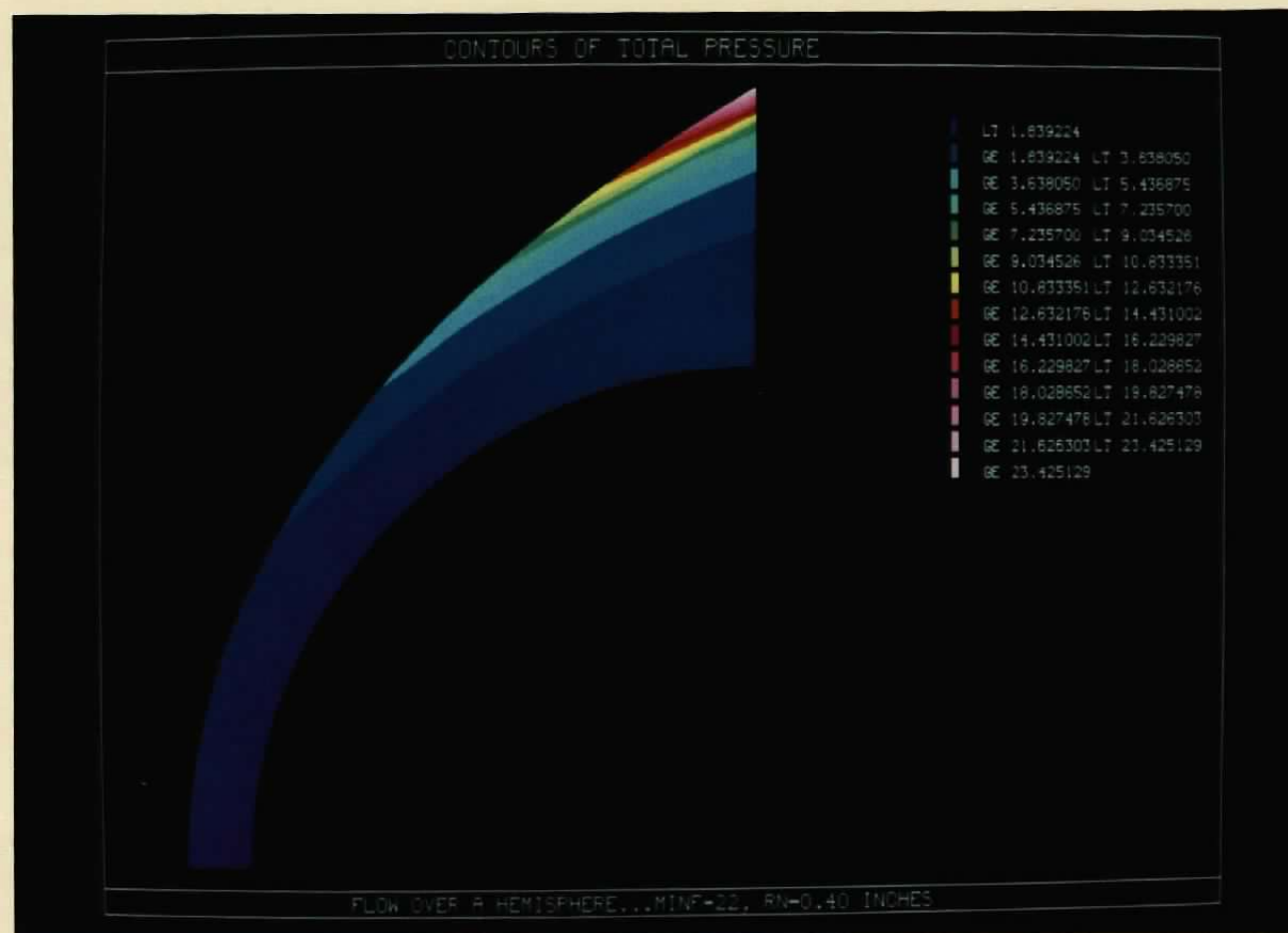
A E D C
14310-86

f. Normalized total pressure
Figure 1. Concluded.

CONTOURS OF PRESSURE

LT 0.156975
GE 0.156975 LT 0.241170
GE 0.241170 LT 0.325365
GE 0.325365 LT 0.409560
GE 0.409560 LT 0.493755
GE 0.493755 LT 0.577950
GE 0.577950 LT 0.662145
GE 0.662145 LT 0.746340
GE 0.746340 LT 0.830535
GE 0.830535 LT 0.914730
GE 0.914730 LT 0.998925
GE 0.998925 LT 1.083120
GE 1.083120 LT 1.167315
GE 1.167315

BLUNT FIN SOLUTION: MINF=2.95
TIME = 4.078

AEDC
14301-86

a. Normalized static pressure
Figure 2. Supersonic viscous flow over a blunt fin protruding from a flat plate (fin plane-of-symmetry).

CONTOURS OF DENSITY

	LT 0.800859
	GE 0.800859 LT 1.159100
	GE 1.159100 LT 1.517341
	GE 1.517341 LT 1.875582
	GE 1.875582 LT 2.233824
	GE 2.233824 LT 2.592065
	GE 2.592065 LT 2.950306
	GE 2.950306 LT 3.308547
	GE 3.308547 LT 3.666788
	GE 3.666788 LT 4.025029
	GE 4.025029 LT 4.383270
	GE 4.383270 LT 4.741512
	GE 4.741512 LT 5.099753
	GE 5.099753

BLUNT FIN SOLUTION: MINF=2.95
TIME = 4.078

A E D C
14302-86

b. Normalized density
Figure 2. Continued.

CONTOURS OF TEMPERATURE

LT 0.402770
GE 0.402770 LT 0.453266
GE 0.453266 LT 0.503761
GE 0.503761 LT 0.554257
GE 0.554257 LT 0.604752
GE 0.604752 LT 0.655248
GE 0.655248 LT 0.705743
GE 0.705743 LT 0.756239
GE 0.756239 LT 0.806734
GE 0.806734 LT 0.857230
GE 0.857230 LT 0.907725
GE 0.907725 LT 0.958221
GE 0.958221 LT 1.008716
GE 1.008716

BLUNT FIN SOLUTION: MINF=2.95
TIME = 4.078

AEDC
14303-86

c. Normalized static temperature
Figure 2. Continued.

AEDC-TR-86-40

CONTOURS OF MACH NUMBER

LT 0.217475
GE 0.217475 LT 0.434183
GE 0.434183 LT 0.650891
GE 0.650891 LT 0.867599
GE 0.867599 LT 1.084307
GE 1.084307 LT 1.301015
GE 1.301015 LT 1.517723
GE 1.517723 LT 1.734431
GE 1.734431 LT 1.951139
GE 1.951139 LT 2.167848
GE 2.167848 LT 2.384556
GE 2.384556 LT 2.601264
GE 2.601264 LT 2.817972
GE 2.817972

BLUNT FIN SOLUTION: MINF-2.95
TIME - 4.078

A E D C
14304-86

d. Local Mach number
Figure 2. Concluded.
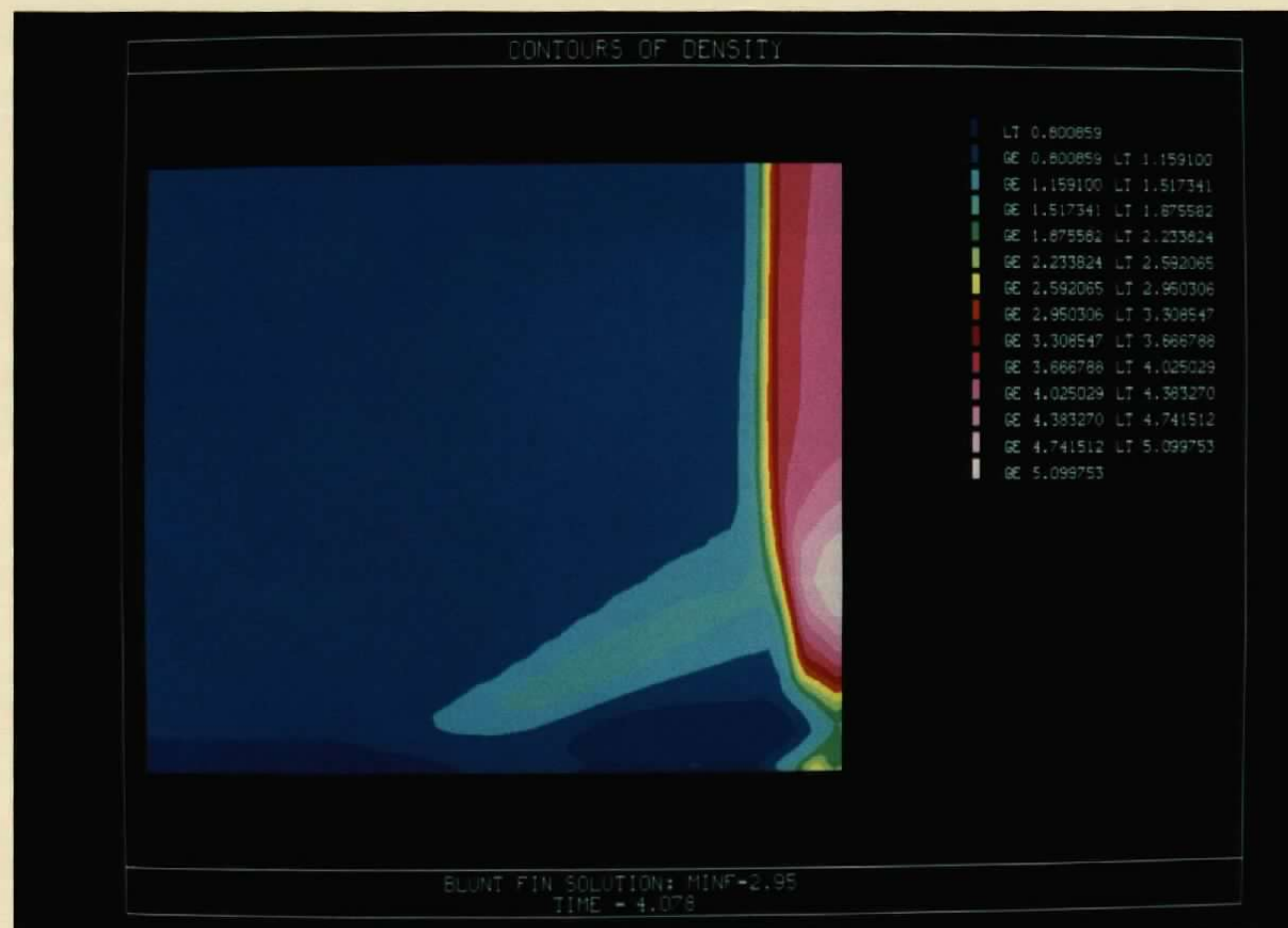
AEDC
14305-86

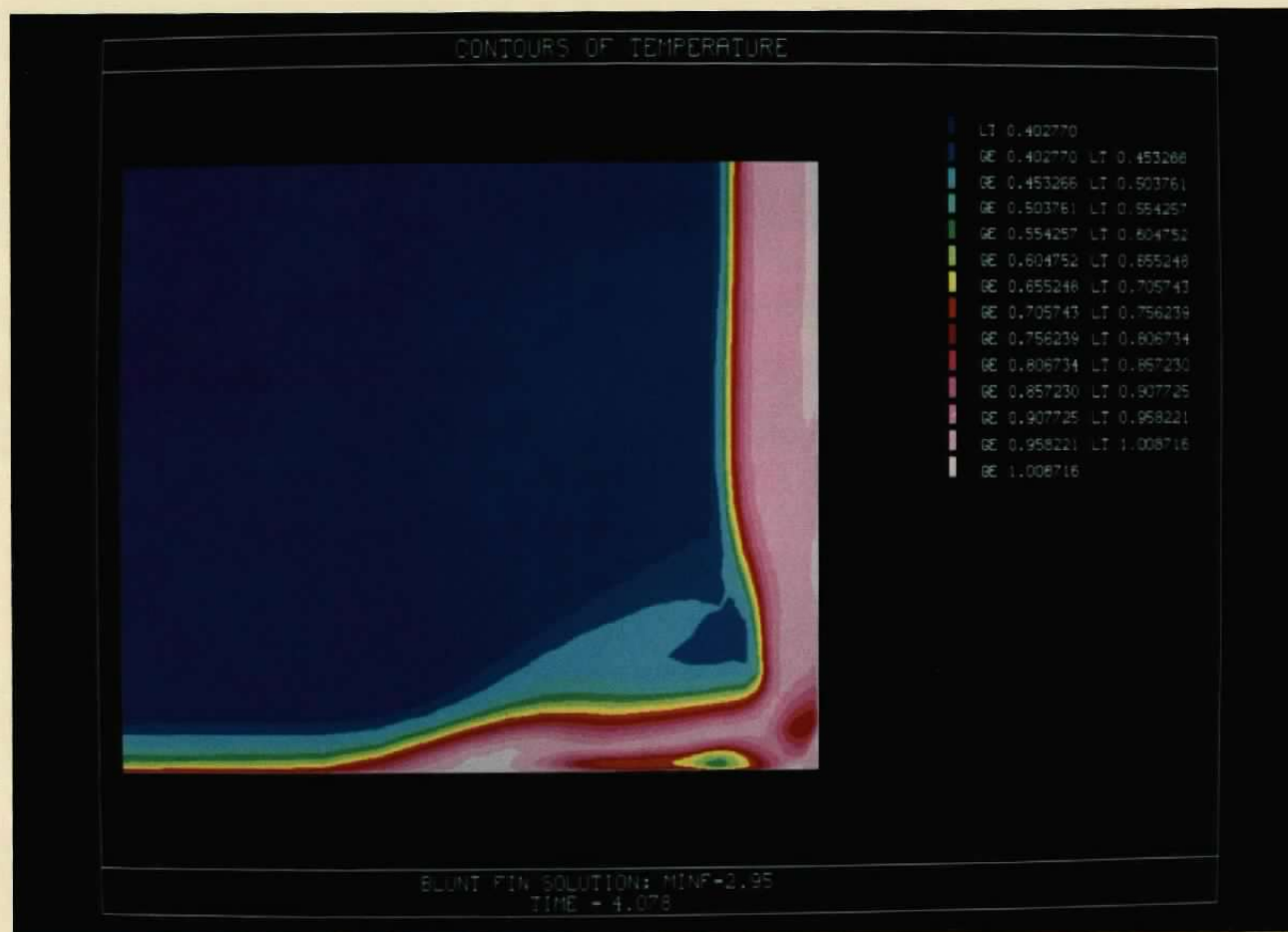a. Normalized static pressure

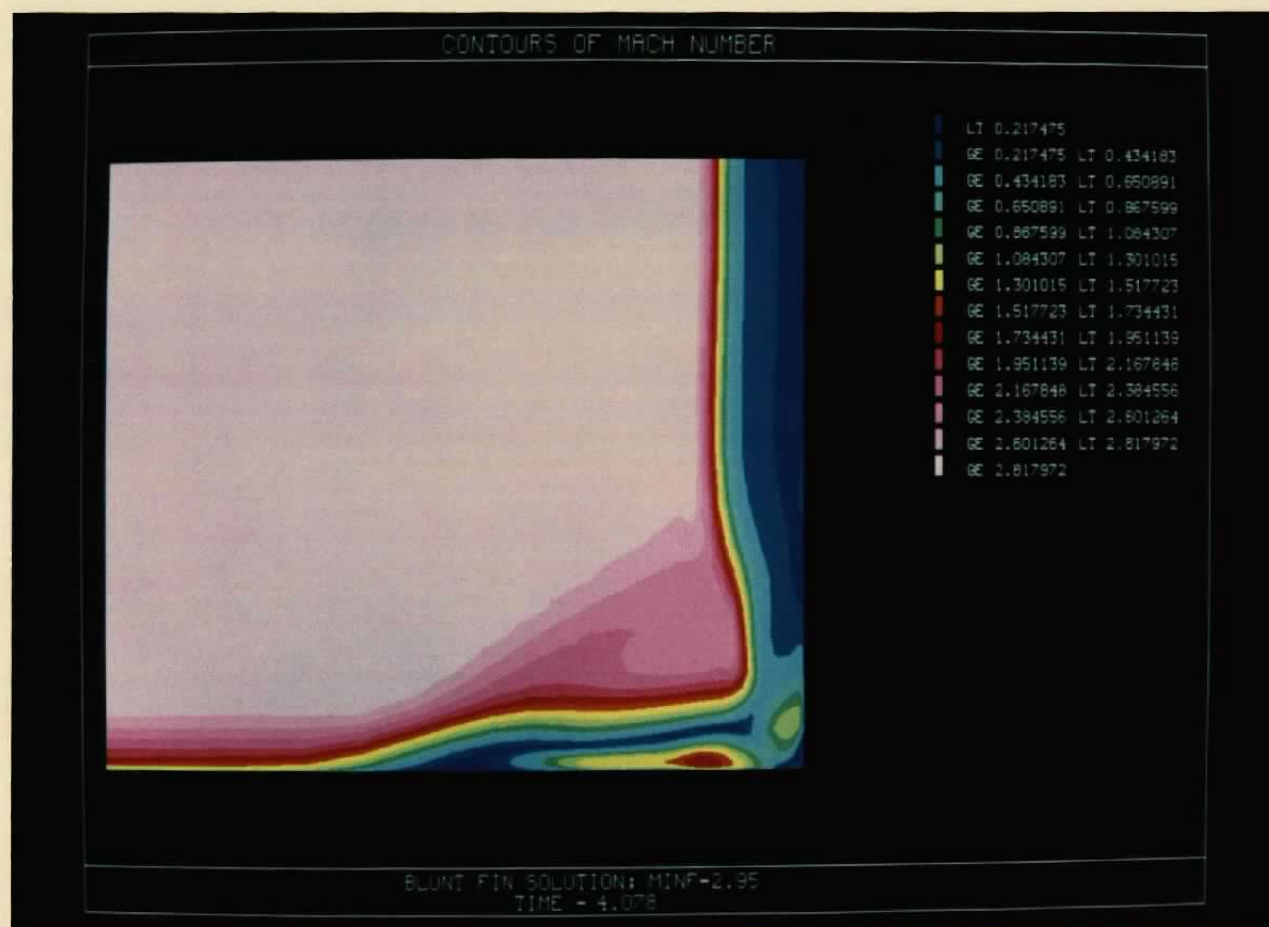Figure 3. Supersonic viscous flow over a blunt fin protruding from a flat plate (plate surface).

CONTOURS OF DENSITY

	LT 0.587890
	GE 0.587890 LT 0.753230
	GE 0.753230 LT 0.918570
	GE 0.918570 LT 1.083910
	GE 1.083910 LT 1.249250
	GE 1.249250 LT 1.414590
	GE 1.414590 LT 1.579931
	GE 1.579931 LT 1.745271
	GE 1.745271 LT 1.910611
	GE 1.910611 LT 2.075951
	GE 2.075951 LT 2.241291
	GE 2.241291 LT 2.406631
	GE 2.406631 LT 2.571971
	GE 2.571971

BLUNT FIN SOLUTION: MINF=2.95
TIME = 4.078
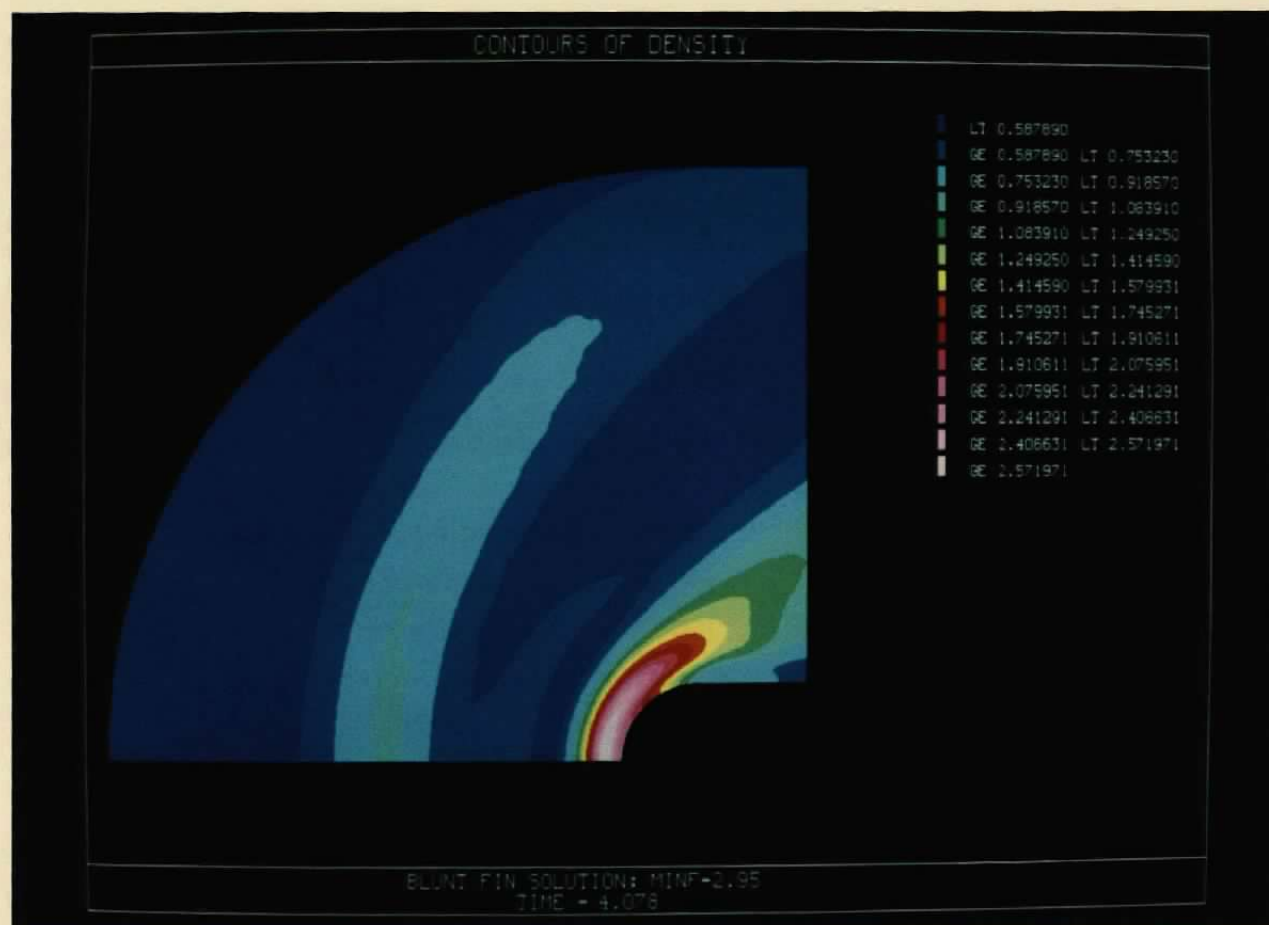
b. Normalized density
Figure 3. Continued.

CONTOURS OF TEMPERATURE

LT 0.767965
GE 0.767965 LT 0.787945
GE 0.787945 LT 0.807924
GE 0.807924 LT 0.827903
GE 0.827903 LT 0.847882
GE 0.847882 LT 0.867861
GE 0.867861 LT 0.887840
GE 0.887840 LT 0.907819
GE 0.907819 LT 0.927798
GE 0.927798 LT 0.947777
GE 0.947777 LT 0.967756
GE 0.967756 LT 0.987735
GE 0.987735 LT 1.007714
GE 1.007714

BLUNT FIN SOLUTION: MINF-2.95
TIME = 4.076
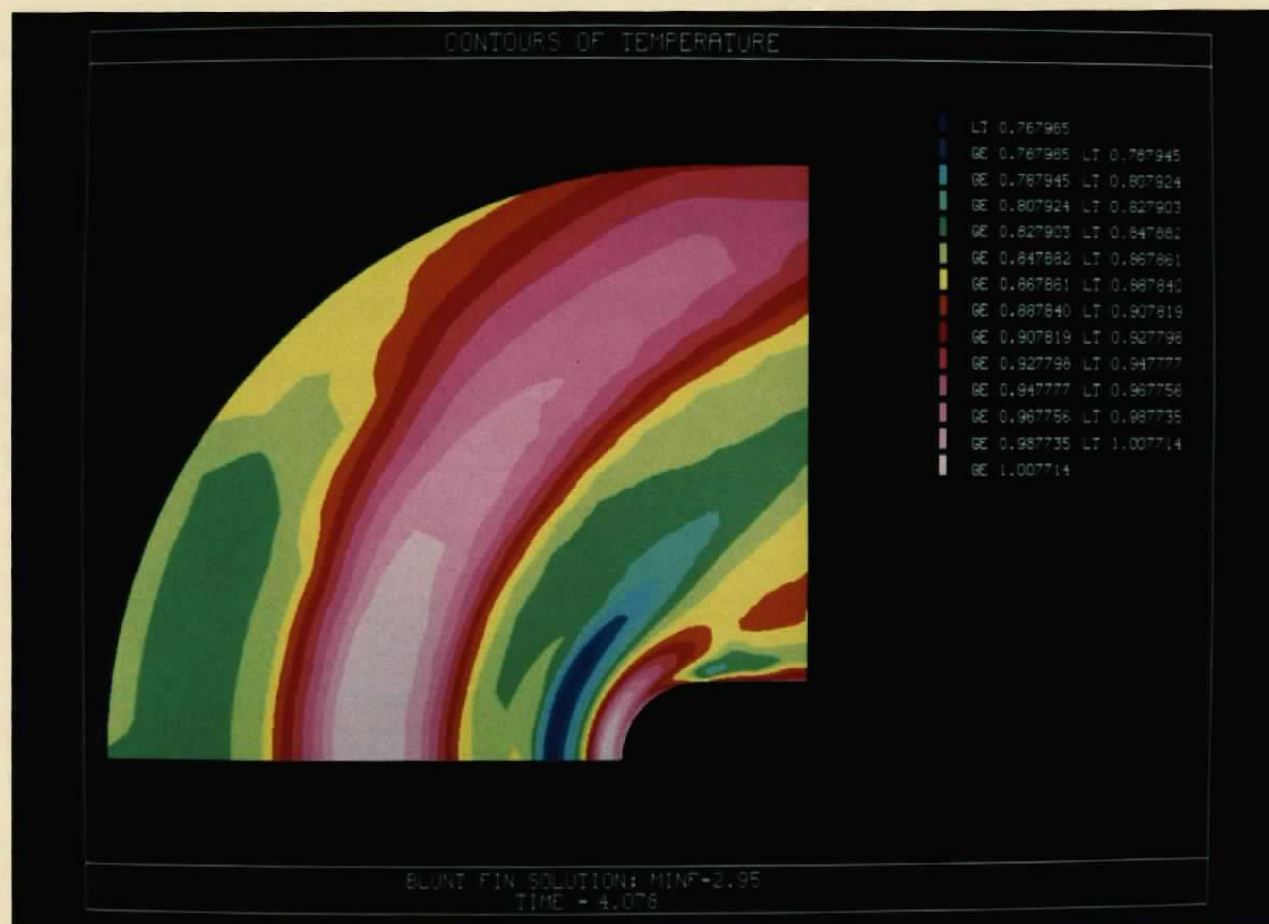
AEDC
14308-86

c. Normalized static temperature
Figure 3. Continued.

CONTOURS OF MACH NUMBER

	LT 0.184709
	GE 0.184709 LT 0.274093
	GE 0.274093 LT 0.363478
	GE 0.363478 LT 0.452862
	GE 0.452862 LT 0.542247
	GE 0.542247 LT 0.631631
	GE 0.631631 LT 0.721016
	GE 0.721016 LT 0.810400
	GE 0.810400 LT 0.899785
	GE 0.899785 LT 0.989169
	GE 0.989169 LT 1.078554
	GE 1.078554 LT 1.167938
	GE 1.167938 LT 1.257323
	GE 1.257323

BLUNT FIN SOLUTION: MINF-2.95
TIME - 4.078

45

A E D C
14309-86

d. Local Mach number
Figure 3. Concluded.

CONTOURS OF PRESSURE

	LT 0.103006
	GE 0.103006 LT 0.168319
	GE 0.168319 LT 0.233632
	GE 0.233632 LT 0.298944
	GE 0.298944 LT 0.364257
	GE 0.364257 LT 0.429570
	GE 0.429570 LT 0.494883
	GE 0.494883 LT 0.560196
	GE 0.560196 LT 0.625508
	GE 0.625508 LT 0.690821
	GE 0.690821 LT 0.756134
	GE 0.756134 LT 0.821447
	GE 0.821447 LT 0.886759
	GE 0.886759

GJNI FLOW FIELD, MINF=15.8, PR=1.15

AEDC
7847-86

a. Normalized static pressure
Figure 4. Hypersonic viscous gas jet nosetip flow.

CONTOURS OF DENSITY

■	LT 5.375470
■	GE 5.375470 LT 9.865998
■	GE 9.865996 LT 14.356522
■	GE 14.356522 LT 18.847048
■	GE 18.847048 LT 23.337575
■	GE 23.337575 LT 27.828101
■	GE 27.828101 LT 32.318627
■	GE 32.318627 LT 36.809153
■	GE 36.809153 LT 41.299680
■	GE 41.299680 LT 45.790206
■	GE 45.790206 LT 50.280732
■	GE 50.280732 LT 54.771258
■	GE 54.771258 LT 59.261785
■	GE 59.261785

GJNT FLOW FIELD, MINF=15.8, PR=1.15

49

A E D C
7848-86

AEDC-TR-86-40
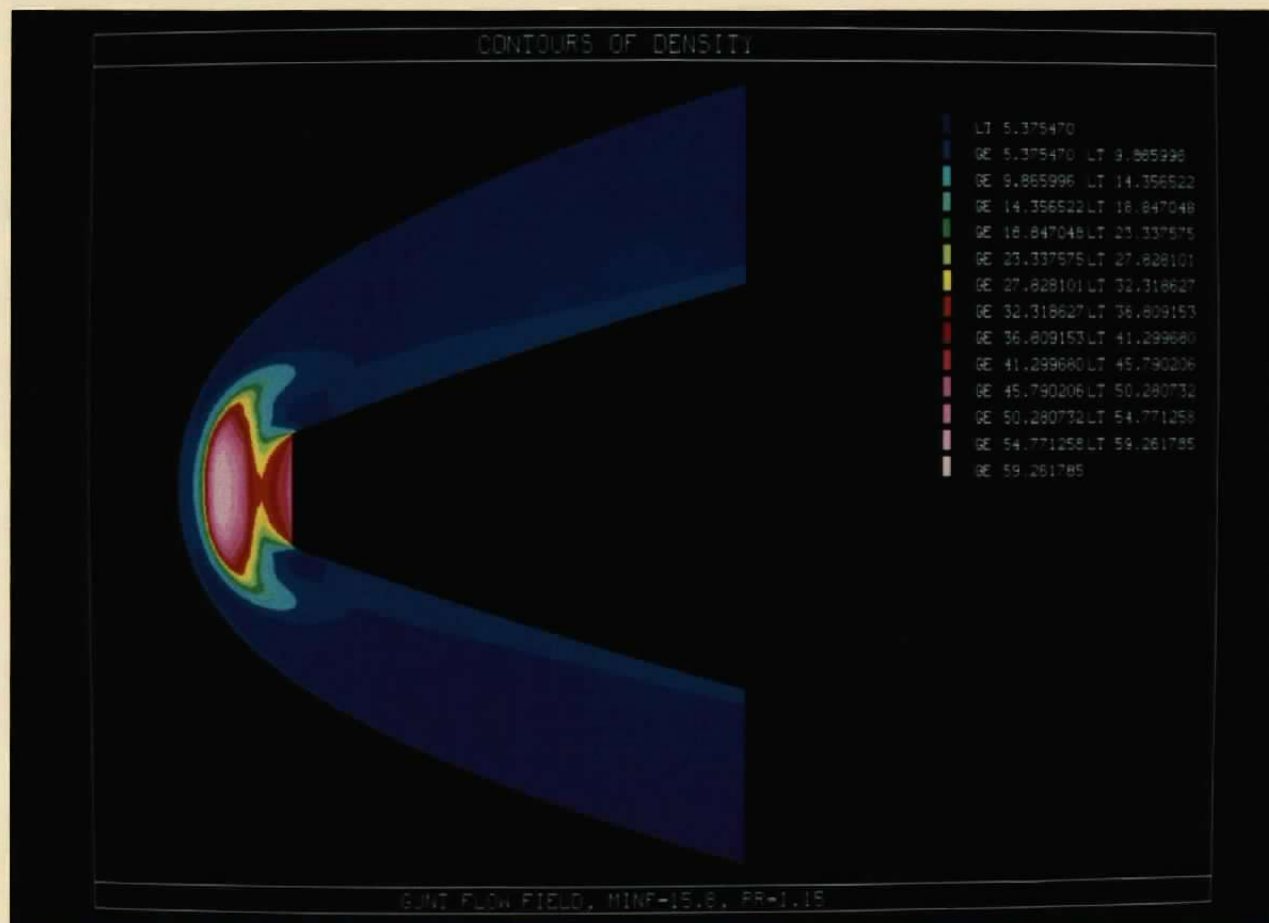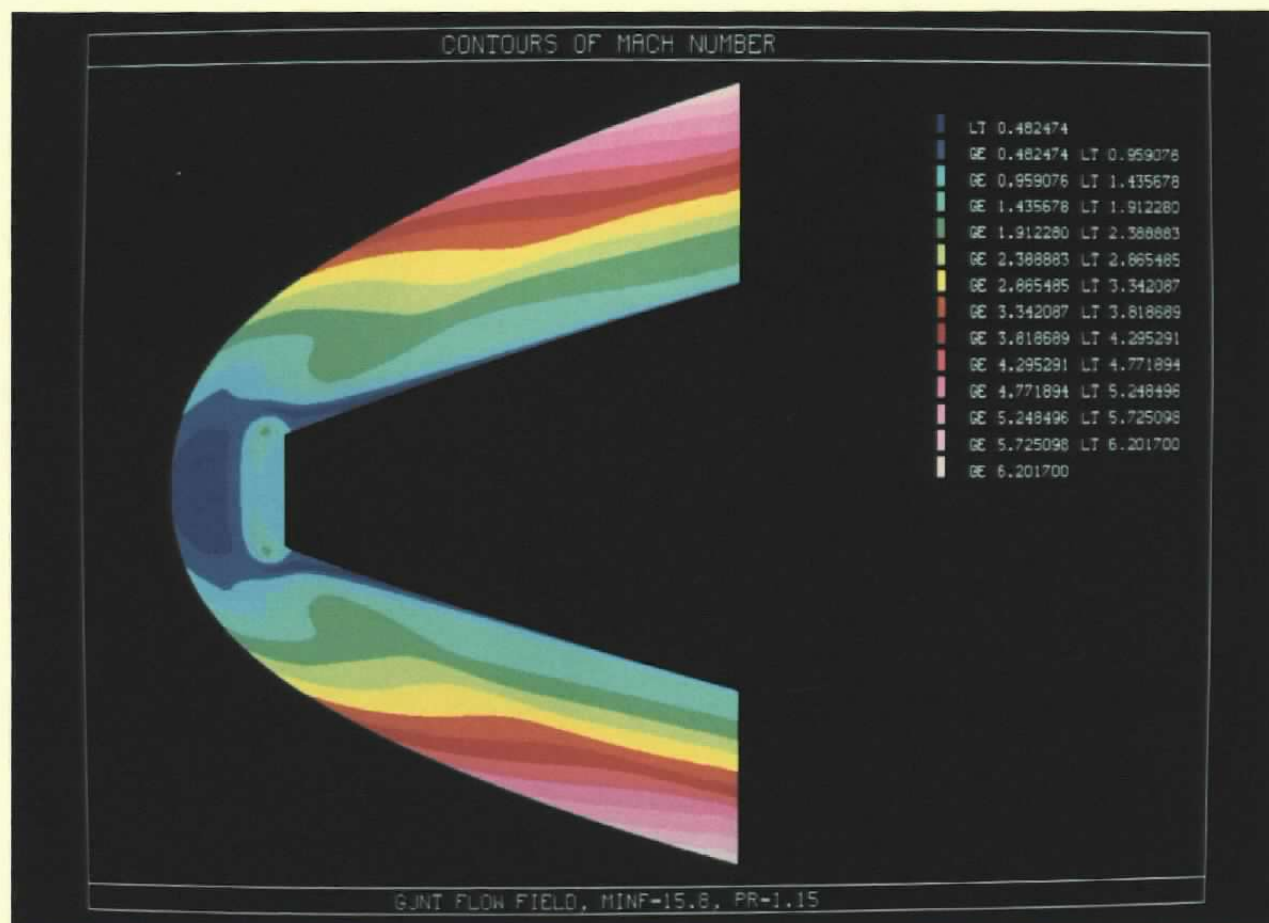
b. Normalized density
Figure 4. Continued.
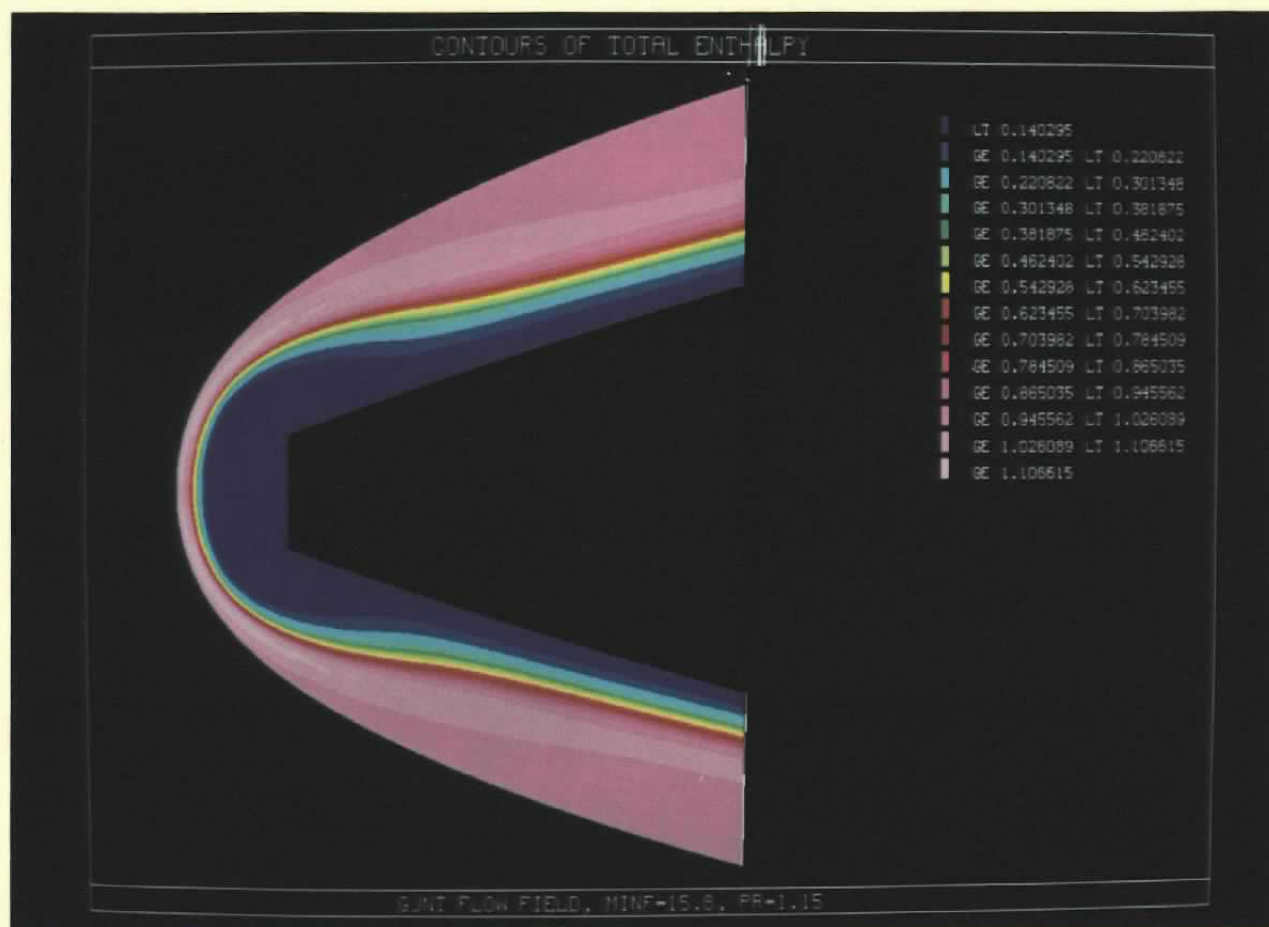
c. Normalized total enthalpy

Figure 4. Continued.

d. Local Mach number

Figure 4. Concluded.

NOMENCLATURE

delta   Increment of contour level

e   Energy per unit volume, normalized by $\varrho_\infty U_\infty^2$

GE   Greater than or equal to

H   Enthalpy, normalized by H_{o_∞}

I   Index used in Eq. (1)

J   Grid point index in the longitudinal direction of the general plotting domain

JMAX   Total number of grid points in the longitudinal direction of the general plotting domain

K   Grid point index in the normal direction of the general plotting domain

KMAX   Total number of grid points in the normal direction of the general plotting domain

LT   Less than

M   Mach number

max   Maximum contour level

min   Minimum contour level

MINF   Free-stream Mach number

N   Upper index used in Eq. (1)

n   Number of contour levels or color number

PR   Jet pressure ratio

Re   Reynolds number

Rn   Nose radius, inches

s   Entropy, normalized by $s_\infty \gamma M_\infty^2$

T   Static temperature, normalized by T_{o_∞}

TIME   Elapsed integration time in BLUNTFIN code, normalized by the number of characteristic lengths traveled with the free-stream velocity

U   Total velocity, normalized by U_∞

u, v, w   Cartesian velocity components, normalized by U_∞

x, y, z   Cartesian coordinates of grid points, user-defined dimensions

γ Ratio of specific heats

ϱ Density, normalized by ϱ_∞

SUBSCRIPTS

cr   Critical value

o, t   Total quantities

∞ Free-stream quantities